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Valorising Insect, Plant and Microbial Protein Sources for Sustainable Livestock

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The rising demand for animal derived proteins and conventional livestock feed production systems has had severe environmental impacts which required radical solutions to ensure sustainable and resilient food systems. This review objectively assesses insect-derived, plant-based and microbial proteins as alternative feed components to address sustainability issues. Insect proteins, especially black army fly larvae and mealworms, are digestible, have strong amino acid profiles, and can efficiently recycle organic waste into high-quality feed, making them competitive and sustainable alternatives to fishmeal and soybean meal. Plant-based proteins like legumes (peas, faba beans) and oilseeds (canola, rapeseed) are scalable and environmentally friendly alternatives, reducing dependence on resource-intensive feedstock while improving soil health and reducing greenhouse gas emissions. Microbial proteins, manufactured by modern fermentation methods using agricultural leftovers, offer an adaptable strategy for waste valorisation and emissions reduction. Alternative proteins have great potential, but scalability, regulatory complexity, and consumer acceptance are obstacles. These challenges require genetic engineering, process optimisation and value chain integration breakthroughs. Implementation and scalability require policy interventions like shortened regulatory processes, targeted financial incentives, and inclusive stakeholder participation. This study summarises comprehensive research and practical applications to demonstrate alternative proteins' environmental, economic, and nutritional benefits in livestock feeds. By leveraging advanced technology, circular economy ideas and interdisciplinary collaboration, the animal feed sector can challenge assumptions. This will allow the sector to fulfil expanding global protein consumption while minimising environmental impacts, making alternative proteins the foundation of future-proof agricultural systems.

Keywords: Agricultural by-products, alternatives, animal, livestock diet, protein sources, sustainable solution.

INTRODUCTION

The global livestock sector needs to balance rising food demand with environmental sustainability and economic viability (Van *et al.,* 2015). The world population will reach more than 9.7 billion by 2050, increasing demand for animal-based protein by over 70% (Magdy, 2024). Traditional feed sources like soybean meal and fishmeal are already depleting resources. Deforestation from soybean production, especially in the Amazon, has disrupted ecosystems and released large carbon emissions (Mulumpwa, 2018; Voora *et al.,* 2020). However, fishmeal manufacturing has caused overfishing and marine biodiversity loss, affecting aquatic ecosystems (Shea, 2024). Economic limitations and environmental damage arising from conventional feed sources have increased concerns for livestock production. Global soy and fishmeal price instability contributes to cattle producers' financial problems (Cottrell, 2020). Heavy use of monoculture crops like soy causes supply chain disruptions due to diseases, pests and climate change (Zou *et al.,* 2024). In response to these challenges, actions are required to explore sustainable protein alternatives, capable of supporting the livestock sector while minimizing environmental impact. Insect-based proteins efficiently convert feed into biomass while requiring less land and water resources comparatively soy-based feeds (Jensen *et al.,* 2021; Kurečka *et al.,* 2021). Black soldier fly larvae and mealworms can be commercially produced as animal feed ingredients (Abd El-Hack *et al.,* 2020). Due to their temperature adaptability and lesser environmental impact than soybeans, legume-based proteins like lupins and peas are also popular. Microbial proteins from innovative fermentation technologies are another sustainable feed production frontier. These proteins provide high-quality feed components and promote circular economy models using straw or whey (Matassa *et al.,* 2016). Genetic engineering and biotechnology are also being utilized to improve the amino acid profile of alternative proteins, making them more valuable for the livestock sector (Wu and Bazer, 2019). This

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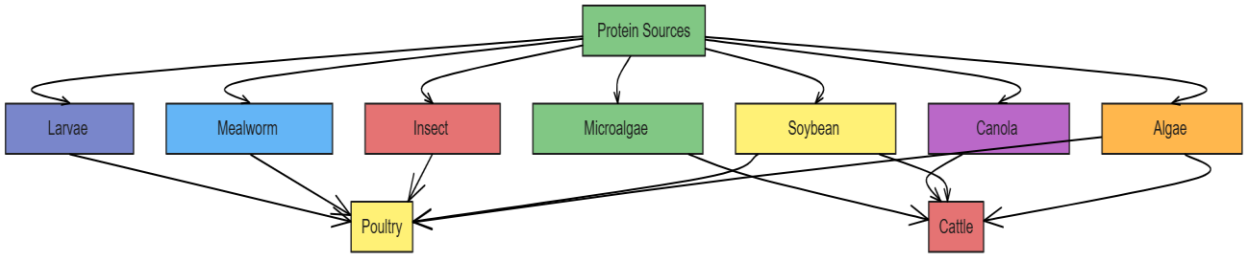

Figure 1. Different sources of alternate proteins for livestock feeds.

review analyses thoroughly the environmental, economic and nutritional impacts of alternative protein sources in livestock diets, emphasizing crucial adoption challenges and prospective solutions. This article advises stakeholders on sustainable animal agriculture development using current research and industry insights.

Types of Alternative Proteins

***Insect-based proteins*:** Insect-based proteins are innovative alternatives due to the high nutritional value and ecological sustainability. Black soldier fly larvae (BSFL), mealworms and crickets are used because they have high protein levels and beneficial amino acids (Hancz *et al.*, 2024). Black soldier fly pupae contain up to 46% crude protein, essential fatty acids, vitamins, and minerals, providing cattle with a balanced nutritional profile (Abd El-Hack *et al.*, 2020). They can also be grown on organic waste to produce high-quality protein, reducing waste and encouraging the circular economy.

Crickets boost feed conversion and weight increase in poultry diets (Bawa *et al.*, 2020). Mealworms have been used to partially replace fishmeal in aquaculture diets, sustaining fish growth and health (Shafique *et al.*, 2021). Benefits include insect production efficiency. Insects utilise less space, water, and feed than animal protein, according to research. Insect farming produces less GHG than cattle protein feeds (Boakye-Yiadom *et al.*, 2022).

Proteins derived from insects are currently used in aquaculture feeds, which include prawns, tilapia, and salmon. These applications reduce fishmeal use and increase aquaculture sustainability. Due to chitin, a bioactive component in insect exoskeletons that boosts immunity, insect-based meals improve gut health in chickens (Malematja *et al.*, 2023). The insect protein sector confronts scalability, consumer perception, and regulatory issues despite these encouraging improvements. Standardising production and obtaining feed clearances are essential for adoption. However, rapid insect farming technology developments and rising investments suggest future expansion. Alongside insect proteins, plant-based alternatives also contribute to a sustainable solution. For nutritional and ecological reasons, plant-based proteins are a staple of sustainable animal feed. In contrast to insect proteins, plant-based proteins depend on nitrogen-fixing crops, minimizing the reliance on synthetic fertilizers.

***Plant based protein*:** Plant-based proteins come from legumes like peas, lupins, and faba beans and oilseed byproducts like canola and sunflower meals (Kumar *et al.*, 2022). Nitrogen-fixing by these plentiful crops minimises synthetic fertiliser use (Kebede, 2021). The protein content of peas is 25% and they are rich in lysine, an important amino acid found in cereal grains. Their versatility makes them a suitable option for poultry and swine. Additionally, extrusion and fermentation reduce anti-nutritional factors (ANFs) like tannins and trypsin inhibitors which lower the digestibility in plant proteins, thereby improving digestibility (Poutanen *et al.*, 2022).

Compared to peas having 25% protein, lupins offer a better protein content of up to 40% making them a valuable choice for livestock (Malarvizhi *et al.*, 2024). Their resilience to arid climate and poor soils makes them a promising crop. They boost milk production and growth in ruminants, according to studies. To use in non-ruminants, alkaloids, which are bitter, must be processed (Mukisira, 1994). Another important legume, faba beans, provide protein and carbohydrates for energy and nutrition. Research shows that replacing soybean meal with faba beans in poultry diets maintains growth performance and feed efficiency (Rahate *et al.*, 2021). Canola and sunflower oilseed meals enhance plant-based proteins (Kumar *et al.*, 2024). Canola meal boosts protein and milk production in dairy cattle. Its low ANFs ensure it is a dependable feed additive (Huhtanen *et al.*, 2011). Sunflower meal has around 32 percent protein and is a cost-effective option for ruminants. Its high fiber content limits application in monogastric, but appropriate processing can resolve this issue (Boudalia *et al.*, 2024). Soy protein concentrates and lucerne protein extracts are recognized as viable protein sources. Soy protein concentrates are processed to reduce anti-nutritional factors and offer up to 70% protein content, making them popular in aquaculture feeds. Alfalfa protein extracts, rich in bioactive compounds, are being studied as sustainable additives to boost growth and immunity in livestock. Plant-based proteins offer vital nutrients for livestock and support sustainable farming. Using these proteins in feed formulations helps the livestock industry reduce environmental impact and offers economic and nutritional benefits.

***Microbial-derived proteins*:** Microbial-derived proteins, or single-cell proteins (SCP), offer a sustainable approach to

Table 1. Different protein feed sources, their use in various livestock systems, and their efficiency.

Protein Source	Livestock	Application	Efficiency and Outcomes	References
Insect-Based Proteins	Poultry, Aquaculture	Used as a partial or complete replacement for fishmeal and soybean meal in poultry and fish diets.	- High digestibility (80-90%) in poultry and fish. - Enhanced growth performance and feed conversion ratio (FCR).	(Devic, 2016; Sajid *et al.*, 2023)
Black Soldier Fly Larvae	Swine, Poultry	Integrated as a protein-rich feed ingredient, particularly for growing pigs and broilers.	- Comparable amino acid profile to fishmeal. - Supports growth and reduces reliance on traditional protein sources.	(Abd El-Hack *et al.*, 2020; Altmann, 2020)
Mealworms	Poultry, Aquaculture	Incorporated into feeds for laying hens and farmed fish.	- Improved egg production in hens. - Maintains growth rates in aquaculture species such as tilapia and salmon.	(Veldkamp *et al.*, 2023)
Plant-Based Proteins	Ruminants, Poultry, Swine	Replacement of soybean meal with legumes (peas, faba beans) or oilseeds (canola, rapeseed).	- Maintains growth performance in poultry with 30-50% replacement. - Improves soil fertility through legume rotation.	(Babatunde *et al.*, 2021)
Canola Meal	Dairy Cattle	Substituted for soybean meal in lactating cow and swine diets.	- Increased milk yield in dairy cows. - Reduced nitrogen excretion compared to soybean meal.	(Maxin *et al.*, 2013)
Microbial Proteins	Ruminants, Aquaculture	Derived from single-cell organisms using fermentation processes.	- SCP supports up to 20% of dietary protein needs. - Lowers greenhouse gas emissions by 10-20% in aquaculture systems.	(Sharif *et al.*, 2021; Onyeaka *et al.*, 2022)
Algal Proteins	Poultry, Ruminants	Incorporated as a source of bioactive compounds and omega-3 fatty acids in feed.	- Improves feed efficiency and enriches fatty acid profiles in eggs and milk. - Suitable for fish diets at 10-15% levels.	(Kaur and Singh, 2024)
Seaweed Meal	Ruminants, Poultry	Used as a protein and mineral source in sheep and chicken diets.	-Boosts sheep immunity and productivity. -Cuts methane emissions in ruminants by 30%.	(Makkar *et al.*, 2016)
Fermented Soy Products	Swine, Poultry	Improves digestibility by breaking down anti-nutritional factors in soy products.	-More digestible than raw soybean meal. -Promotes growth in early stage pigs.	(Van *et al.*, 2013)

livestock nutrition. SCP from microorganisms such as algae, bacteria, and fungi offers high protein, fast production, and lower environmental impact. Proteins are produced through controlled fermentation using agricultural or industrial byproducts like whey, molasses, or lignocellulosic biomass (Asiri and Chu, 2022). Single cell protein has a notable nutritional profile, with protein content ranging from 50% to 80%, depending on the microorganism used (Sharif *et al.*, 2021). Single cell protein contains vital amino acids, vitamins, and bioactive compounds that enhance livestock health and performance. Fungal derived SCP from *Fusarium venenatum* improves gut health in poultry due to its high digestibility (Amara and El-Baky, 2023).

Production of microbial proteins on non-arable land reduces competition with food crops, ensuring resource efficiency. Single cell protein production uses an efficient fermentation process that requires fewer natural resources than traditional protein sources.

Single cell protein production not only provides environmental advantages but also adheres to circular economy principles by converting waste materials into valuable feed ingredients, thus minimising inefficiencies within the food system.

As a scalable alternative for sustainable livestock feeding, fermentation-based protein production is emerging. By optimising bioreactor microbe cultivation, protein yield and quality may be controlled. Single cell protein production has become more efficient and versatile due to genetic engineering and metabolic optimisation. Genetically engineered yeast strains are being created to synthesise amino acids and bioactive compounds according to livestock species' diets (Shurson, 2018). Single cell protein adoption is hindered by production costs, scalability, and regulatory permission. Fermentation technology advances and alternative protein sector investments should overcome these barriers. A reliable and environmentally friendly alternative to standard feed ingredients, microbial-derived proteins are set to transform sustainable animal production.

Benefits of Alternative Proteins

***Environmental impact*:** Alternative proteins in livestock diets can reduce animal agriculture's environmental impact (Green *et al.*, 2022). Feed production from traditional resources plays a major role in the emission of carbon dioxide, methane and nitrous oxide. Alternative proteins from insect-based and microbial feed sources, *considerably reduce* these emissions by decreasing reliance on high resource demanded traditional feeds *(*Gómez *et al.*, 2019*;* Lee *et al.*, 2024*).* Black soldier fly

Table 2. Challenges in adoption of alternative proteins.

Category	Challenges	Details	Citations
Regulatory and Policy Barriers	Complex regulatory frameworks	Insect-based and microbial proteins need thorough safety assessments for approval. Regulatory processes can delay market entry, especially regarding allergens, contaminants, and heavy metals in production.	(Can *et al.*, 2023)
	Lack of global harmonization	Disparate regulatory standards across regions hinder international trade and adoption of alternative proteins, complicating supply chain management for global markets.	(Gereffi and Lee, 2009)
Consumer Perception and Market Acceptance	Misconceptions about safety and nutrition	Consumer education is required to address myths regarding the safety and nutritional adequacy of alternative proteins, which can deter adoption by producers and buyers.	(Onwezen *et al.*, 2021)
	Limited awareness of benefits	A lack of communication on the environmental and health benefits of alternative proteins reduces their acceptance among consumers and stakeholders.	
	Scalability of production	Transitioning from small-scale to industrial-scale operations is challenging due to high capital requirements, technical expertise, and the need for automation.	
Technical and Logistical Limitations	Infrastructure and supply chain constraints	Unestablished supply chains for insect and microbial proteins raise costs and complicate distribution. Transport, storage, and processing infrastructures are essential for large-scale adoption.	(Grasso *et al.*, 2019)
	Quality control and consistency	Consistent quality check in batches is crucial for livestock health and performance. Challenges include substrate quality variations for microbial proteins and the nutritional profile of insect feeds.	
	High production costs	High production costs of some alternative proteins, like fermentation-based SCP, hinder their competitiveness with traditional feed ingredients, despite environmental benefits.	

larvae use less water and land than soybean farming, while insect farming needs even less. Fermentative microbial protein production utilizes non-arable land, converting straw and whey into valuable feed components, enhancing circular economy principles (Siddiqui *et al.*, 2022). Legumes such as peas and faba beans fix nitrogen, benefiting the ecosystem. This removes the need for synthetic fertilizers, which raise nitrous oxide and harm the soil. Crops can be grown in rotation to enhance soil health and resist pests and diseases (Svanes *et al.*, 2022). Alternative feed ingredients can lower deforestation, biodiversity loss, and water pollution in cattle farming. Switching from soybean meal to insect or microbial proteins can lessen soybean farming in sensitive areas like the Amazon. It protects biodiversity and stops significant carbon release.

***Animal health and performance*:** Alternative proteins enhance digestibility and nutrient absorption, boosting animal health and performance. Black soldier fly larvae proteins have improved digestibility due to a balanced amino acid profile that meets livestock dietary needs (Mshayisa *et al.*, 2022). Research shows that insect meal in broiler diets improves feed conversion by 0.64 to 7%, while fermentation-derived proteins boost milk production in dairy cattle compared to soybean meal (Godoy *et al.*, 2018; Moula and Detilleux, 2019). *Insect and microbial proteins show better digestibility due to the well-balanced amino acid profiles, which strongly correspond to livestock dietary requirements compared to soybean meal (*Moula and Detilleux, 2019*). Research indicates that insect meal in broiler diets improves FCR by 0.64% to 7%, while fermentation-derived proteins improve milk production in dairy cattle (*Mshayisa *et al.*, 2022*).* Better digestibility boosts feed efficiency and reduces total feed intake, resulting in cost savings and improved resource use. Some alternative proteins contain bioactive compounds such as chitin that boost animal immune function. Insect proteins have prebiotic chitin that improve gut health by lowering *digestive disorders up to 15%* in chickens and pigs (Kipkoech, 2023).

***Economic advantages*:** *Alternative proteins also provide significant economic advantages, along with environmental benefits. With increasing prices of* soybean meal and fishmeal, alternative proteins are seeking more attention due to cost-effectiveness and increasing global protein demand. Alternative proteins utilize agricultural and organic waste and non-arable land, making them cost-effective (Parisi *et al.*, 2020). Insect and microbial proteins can lower feed costs when produced at scale. A case study on a Southeast Asian black army fly larvae farm showed 40% cost savings compared to soybean meal by *lowering raw material expenses* (Kim *et al.*, 2021). Microbial protein synthesis in Europe lowers feed costs by utilising agricultural leftovers such as wheat straw and molasses for fermentation (Bajić *et al.*, 2022). Black soldier fly larvae can be cultivated on organic waste to create high-value protein products at a fraction of the cost of traditional feed ingredients (Van *et al.*, 2015). In pilot tests, adding black soldier fly larvae to chicken diets reduced feed expenditures (Leipertz *et al.*, 2024). Costs are falling as fermentation technology for microbial proteins

becomes more scalable and efficient (Khoshnevisan *et al.,* 2022).

Alternative proteins lessen livestock producers' dependence on traditional feed markets, reducing price volatility and supply chain disruptions. Diversity increases resilience to environmental and geopolitical threats, delivering a secure and sustainable feed source (Lisboa *et al.,* 2024). *This minimizes influences of price fluctuations and trade restrictions, maintaining a stability and cost-effective feed supply (*Lisboa *et al.,* 2024*).*

***Advancements in protein production technologies*:** New protein synthesis strategies could revolutionize livestock feeding (Pexas *et al.,* 2023). Genetic engineering can create insect strains with higher protein yields and faster development cycles (Gomes *et al.,* 2012). Athanassiou *et al.* (2024) showed that genetically engineered black soldier fly larvae had enhanced protein profiles and require fewer resources to grow, making them a viable feed component. Transformative fermentation-based microbial protein synthesis optimisation. Scaled continuous bioreactor systems (*maintain steady microbial growth and protein synthesis)* reduce production costs and boost efficiency. Those methods convert agricultural and organic waste into protein, reducing waste and creating feed ingredients (Timm *et al.,* 2015). Microbial proteins are becoming a viable aquaculture and poultry feedstock due to technological advances.

***Integrating alternative proteins into circular economy models*:** Alternative proteins in livestock feed systems are essential for circular economy sustainability. Organic waste streams including post-harvest agricultural wastes and food waste can be used to feed insect rearing or microbial fermentation. This strategy aligns economic and environmental goals by reducing protein production's carbon intensity and waste disposal. These programs need cross-sector ties to grow. Waste management agencies and protein manufacturers have shown that waste streams can be improved for feed (Timm *et al.,* 2015). Biogas facilities and microbial protein producers have developed resource-efficient solutions to close feed production value chains. Collaborative models show protein manufacturing systems can be sustainable at an industrial scale.

***Policy and industry strategies to accelerate adoption*:** Alternative protein integration into livestock feed systems requires strategic legislative interventions and industry-driven initiatives. Regulatory simplification is needed to allow novel feed additives to enter the market. Insect farming infrastructure and fermentation bioreactor subsidies may ease this shift. Stakeholder engagement along the value chain builds trust and acceptance. Informing farmers, feed makers, and consumers about alternative proteins' environmental, economic, and nutritional benefits is crucial to market acceptability. Pilot studies and targeted marketing efforts that demonstrate these innovations' efficacy and safety reduce skepticism and increase uptake.

Protein production technologies, circular economy principles, and strong policy frameworks can improve animal feed sector sustainability, resilience, and profitability. To adapt to a changing global food situation, feed systems must be redesigned to include different proteins.

***Conclusion*:** The global livestock industry encounters significant challenges in fulfilling the increasing demand of protein-rich diets for livestock, while simultaneously addressing environmental, economic and social issues. Alternative proteins from insects, plants and microbes, represent significant solutions to these challenges by reducing the ecological footprint of traditional livestock feed production, enhancing nutrient efficiency, and strengthening food security. Insect proteins and plant-based proteins exhibit high digestibility and efficient resource utilization, indicating substantial potential in poultry, aquaculture and swine systems. Microbial proteins also offer an innovative approach by utilizing waste materials to produce high-quality feed ingredients. However, the *widespread adoption of alternative proteins requires addressing regulatory and consumer acceptance obstacles. Future research on* improving fermentation techniques *and enhancing the palatability of insect-based feeds is vital for boosting their commercial viability.*

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Policy referred: FAO's Sustainable Animal Diets Policy Guidelines (FAO, 2021),United Nations Sustainable Development Goals (UN SDGs), particularly Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action),OECD Policy Framework for the Bioeconomy (2018).

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